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Solar Drying of *Moringa oleifera* Leaves: A Comprehensive Review on Nutrient Retention and Process Optimization

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Abstract: Solar drying can be a good and sustainable technique of drying nutrient-rich medicinal plants like Moringa oleifera leaves, which are commonly known to contain high levels of vitamins, minerals, antioxidants and bioactive compounds. The moringa leaves, however, are very perishable due to their high moisture content and thus require effective drying methods to preserve their nutritional value. The current review focuses on new developments in solar drying technologies for moringa leaves, with emphasis on nutrient retention, drying performance, and process optimization. Different ways of drying, such as open sun drying, direct, indirect and hybrid solar dryers, are critically discussed. The influence of key drying conditions, such as temperature, airflow velocity and drying time, on moisture removal and heat-sensitive nutrient degradation is addressed. Also, recent optimization methods, such as Response Surface Methodology (RSM), Artificial Neural Networks (ANN) and machine learning methods, are highlighted as having the potential to model, predict and optimize drying performance. The research identifies research gaps, especially the lack of studies on nutrient retention and the unavailability of predictive models to control the process. The way forward in future research is to develop smart solar drying systems that can monitor and optimise in real time to ensure that nutrients are preserved and energy use is as minimal as possible.

Introduction

Medicinal plants have become one of the most discussed topics over the past few years due to the abundance of bioactive substances in their structures and their potential for use in the food, pharmaceutical and nutraceutical markets. One of these is *Moringa oleifera*, the leaves of which are popular due to their outstanding nutritional value, with a high concentration of vitamins (A, C and E) and minerals (iron, calcium, potassium) and protein components, as well as numerous phytochemicals, including flavonoids, phenolics, and antioxidants (Fombang et al., 2021; Sarkar et al., 2022). The compounds have many health benefits, such as anti-inflammatory, antimicrobial and antioxidant properties.

Although nutritionally valuable, fresh moringa leaves are very perishable because of their high moisture content, which enhances the growth of microbes and enzyme degradation. Consequently, one of the most important preservation methods is drying, which prolongs shelf life and keeps it available all year round. Most conventional drying techniques, such as open-sun drying, are still popular in many regions but face various disadvantages, including contamination, reliance on weather and time-consuming and substantial heat losses of heat-sensitive nutrients (Satwase, 2012; Suzauddula et al., 2019).

To break these constraints, solar drying has become a viable option that harnesses renewable energy and offers

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greater control over drying conditions. Sophisticated solar drying techniques, such as direct, indirect, mixed-mode, and hybrid dryers, have been designed to enhance product efficiency and quality. Such systems considerably reduce drying time and improve the preservation of bioactive substances compared with traditional methods (Margarita et al., 2018; Goudjinou et al., 2025).

Drying has a complicated process of heat and mass transfer that depends on various parameters including temperature, the speed of airflow and time of drying. A lack of appropriate management of these parameters may result in the loss of sensitive nutrients such as vitamin C and phenolic compounds, which will eventually affect the quality of dried products (Potisate et al., 2014; Kumar et al., 2020). The optimization of drying conditions is therefore vital to ensuring a balance between efficient moisture removal and maximum nutrient retention.

Over the past few years, statistical and computational analyses, such as Response Surface Methodology (RSM) and Artificial Neural Networks (ANN), have become more commonly used to model and optimize drying processes. Such methods allow the determination of optimal drying conditions and provide predictive models to enhance process efficiency and product quality (Sadadou et al., 2021; Akter et al., 2022). Furthermore, the development of solar dryers and the implementation of technologies such as thermal storage and automatic control have improved the performance and energy efficiency of drying (Jalil et al., 2022; Suresh et al., 2025).

Despite the above achievements in solar drying technologies, there are still research gaps, especially in nutrient-related optimization, real-time control, and predictive modeling of drying performance. The majority of studies focus on moisture removal, although little attention is paid to preserving bioactive compounds and the product's overall quality.

Thus, the purpose of this review is to analyze in detail the solar drying technologies for Moringa oleifera leaves, focusing on drying kinetics, nutrient retention, energy efficiency and optimization methods. The research also identifies gaps in the current state of the art and proposes a path for future developments of enhanced, intelligent and sustainable solar drying systems.

Literature Review

Moringa oleifera leaves have been extensively studied due to their high nutritional and medicinal value. Several researchers have highlighted that these leaves are rich in antioxidants, phenolic compounds, vitamins, and essential minerals, making them suitable for functional food and nutraceutical applications (Fombang et al., 2021; Kumar et al., 2024). However, their high moisture content necessitates efficient drying techniques to preserve their quality and extend shelf life.

Effect of Drying Methods on Moringa Leaves

Various drying methods, including open sun drying, shade drying, oven drying, freeze drying, and solar drying, have been investigated for moringa leaves. Traditional methods such as sun and shade drying are cost-effective but often result in poor product quality due to contamination, long drying times, and significant nutrient degradation (Satwase, 2012; Suzauddula et al., 2019).

Advanced drying techniques such as oven drying and freeze-drying offer better control over drying conditions and improved retention of bioactive compounds. However, these methods are energy-intensive and expensive, limiting their applicability in rural and small-scale settings (Potisate et al., 2014; Iwansyah et al., 2020). In contrast, solar drying provides a balance between cost-effectiveness and quality preservation, making it a viable alternative for agricultural applications (Margarita et al., 2018).

Recent studies have shown that hybrid and indirect solar dryers significantly improve drying efficiency and product quality compared to traditional methods. For instance, indirect solar dryers reduce contamination and allow better control of drying parameters, while hybrid systems enhance drying performance by integrating auxiliary energy sources or thermal storage (Goudjinou et al., 2025; Hegde et al., 2025).

Drying Kinetics and Modeling

Drying kinetics of moringa leaves have been widely studied to understand moisture removal behavior under different drying conditions. Mathematical models such as Page, Henderson and Pabis, and Midilli models are commonly used to describe drying characteristics (Iglesias Díazet al., 2018; Taufan et al., 2020). These models help in predicting drying time, moisture diffusivity, and drying rates.

Experimental studies indicate that drying of moringa leaves predominantly occurs during the falling-rate period, where moisture diffusion is the controlling mechanism (Suzauddula et al., 2019). The effective moisture diffusivity is influenced by temperature, airflow and leaf thickness, and typically increases with higher drying temperatures (Kumar et al., 2024).

Furthermore, hybrid solar drying systems have demonstrated improved drying kinetics due to enhanced heat transfer and uniform airflow distribution, resulting in reduced drying time and improved efficiency (Téllez et al., 2019).

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Table 1. Comparison of Drying Methods for Moringa Leaves.

Drying Method	Advantages	Limitations	Key Findings
Open Sun Drying	Low cost, simple	Contamination, weather dependent, nutrient loss	Poor quality retention (Satwase, 2012)
Shade Drying	Better color retention	Very slow drying	Limited efficiency (Suzauddula et al., 2019)
Oven Drying	Controlled temperature	High energy consumption	Good phenolic retention (Potisate et al., 2014)
Freeze Drying	Best nutrient preservation	Expensive, complex	High antioxidant retention (Iwansyah et al., 2020)
Solar Drying	Eco-friendly, cost-effective	Weather dependent (partially)	Balanced performance (Margarita et al., 2018)
Hybrid Solar Dryer	High efficiency, faster drying	Higher initial cost	Improved drying rate (Goudjinou et al., 2025)

Table 2: Common Drying Models Used for Moringa Leave.

Model	Equation (General Form)	Application	Reference
Page Model	$MR = \exp(-kt^n)$	Best fit for many drying processes	Taufan et al., 2020
Henderson & Pabis	$MR = a \cdot \exp(-kt)$	Simple modeling	Iglesias Díaz et al., 2018
Midilli Model	$MR = a \cdot \exp(-kt^n) + bt$	Highly accurate prediction	Téllez et al., 2019
(MR = Moisture Ratio, k = drying constant, t = time)			

Impact of Drying on Nutritional and Bioactive Compounds

One of the major concerns in drying moringa leaves is the degradation of heat-sensitive nutrients such as vitamin C, phenolics, and antioxidants. Studies have shown that high drying temperatures and prolonged drying times can significantly reduce the concentration of these compounds (Nobossé et al., 2017; Kumar et al., 2020).

Post-harvest treatments such as blanching and pre-treatment methods have been found to influence nutrient retention. While blanching can improve drying efficiency and color retention, it may also lead to partial loss of water-soluble nutrients (Fombang et al., 2021). Similarly, different drying methods result in varying levels of nutrient preservation, with controlled drying techniques generally outperforming traditional methods (Hegde et al., 2025).

Recent research has also emphasized the importance of optimizing drying conditions to maximize the retention of total phenolic content and antioxidant activity. For example, optimization using Response Surface Methodology has been successfully applied to determine optimal drying parameters for preserving bioactive compounds (Akter et al., 2022; Babarabie et al., 2025).

Solar Dryer Design and Technological Advancements

The design of solar dryers plays a crucial role in determining drying efficiency and product quality. Key components such as solar collectors, absorber plates, airflow systems, and insulation significantly influence thermal performance. Innovations in solar dryer design, including the use of selective coatings, fins, and thermal storage materials, have improved heat transfer and drying efficiency (Margarita et al., 2018).

Modern solar dryers are increasingly integrated with sensors, microcontrollers, and automated control systems to monitor and regulate temperature and humidity. For instance, microcontroller-based dual-energy solar dryers have been developed to enhance process control and ensure consistent drying conditions (Jalil et al., 2022).

Additionally, recent advancements include the use of spectral irradiance control to improve color retention and preserve bioactive compounds during solar drying (Delgadillo-Ruiz, 2025). Such innovations highlight the potential of combining engineering design with advanced technologies to improve drying performance.

Optimization and Artificial Intelligence Applications

Optimization of drying parameters is essential to achieve maximum efficiency and product quality. Traditional trial-and-error approaches are time-

consuming and inefficient, leading to inconsistent results. Therefore, advanced optimization techniques such as Response Surface Methodology (RSM) have been widely used to evaluate the interaction effects of drying parameters and identify optimal conditions (Akter et al., 2022).

Artificial Neural Networks (ANN) and machine learning techniques have also gained attention for modeling complex drying processes. These approaches can accurately predict drying behavior and optimize process parameters under varying conditions (Sadadou et al., 2021). AI-based models are particularly useful for real-time monitoring and control of solar drying systems.

Research Gaps Identified from Literature

Despite significant advancements, several limitations remain in the existing literature:

- Lack of precise control over drying parameters in low-cost solar dryers
- Insufficient focus on nutrient retention as a primary output
- Limited application of predictive modeling techniques
- Dependence on experimental and trial-based optimization methods
- Lack of standardized solar dryer designs for medicinal leaves

These gaps highlight the need for integrated approaches combining advanced drying technologies, optimization tools, and intelligent control systems to improve drying efficiency and product quality.

Types of Solar Dryers

Solar dryers are classified based on heat transfer mechanism, air movement, and system configuration. The major types are as follows:

Open Sun Drying (OSD)

Open sun drying is the simplest and most traditional method in which the product is directly exposed to solar radiation and ambient air. Although it is economical and easy to implement, it has major drawbacks, including contamination, dependence on weather conditions, and poor control over drying parameters (Fernandes et al., 2024).

Direct Solar Drying (DSD)

In direct solar drying, the product is enclosed in a transparent chamber and exposed directly to solar radiation. The greenhouse effect increases the internal temperature, enhancing moisture removal. This method provides better protection and improved drying efficiency compared to open sun drying (Fernandes et al., 2024).

Indirect Solar Drying (ISD)

Indirect solar dryers use a separate solar collector to heat air, which is then passed through the drying chamber. Since the product is not exposed to direct sunlight, this method helps preserve color, nutrients, and quality of heat-sensitive materials (Fernandes et al., 2024).

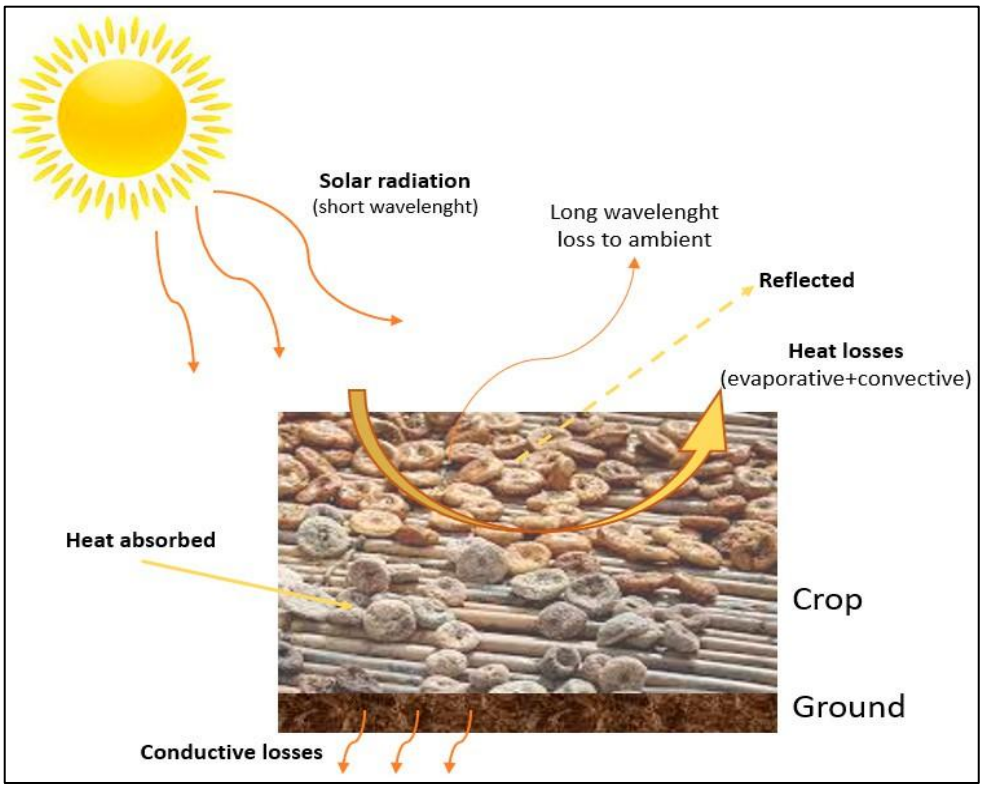

Figure 1. Schematic of the working principle of the open sun drying method.

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Hybrid Solar Drying

Hybrid solar dryers integrate solar energy with auxiliary energy sources such as electricity, biomass, or thermal storage systems. These dryers ensure continuous operation even under cloudy conditions or at night and provide better control over drying parameters (Fernandes et al., 2024).

Current Challenges in Solar Drying of Medicinal Leaves

Even though the technology of solar drying has been greatly improved, various factors still limit its effectiveness, reliability, and widespread use, especially for medicinal leaves such as Moringa oleifera. These issues are linked with process control, product quality,

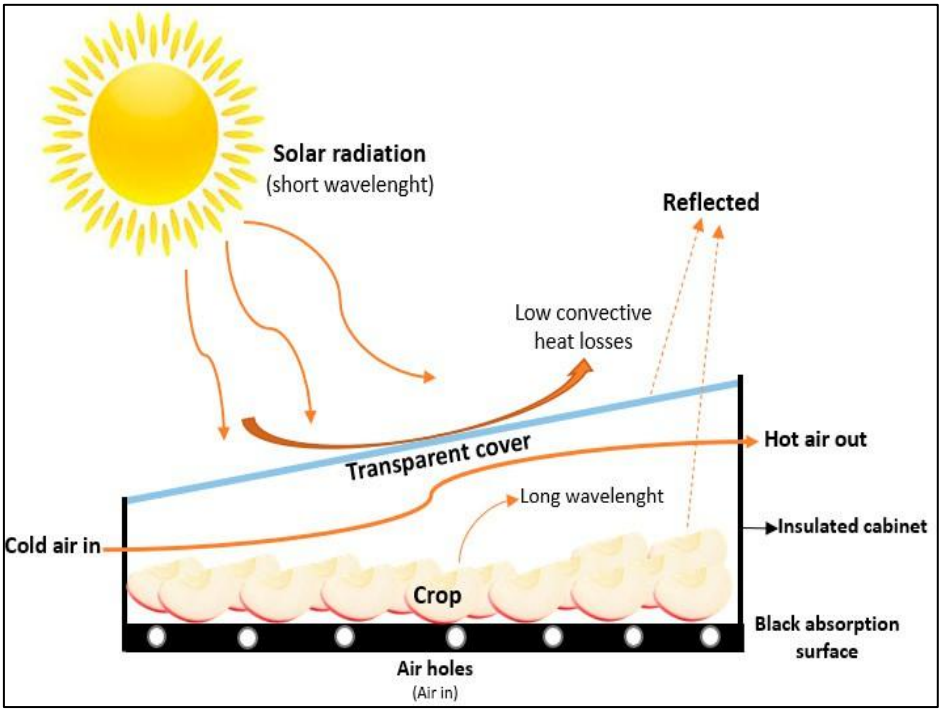

Figure 2. Schematic of working principle of direct drying method.

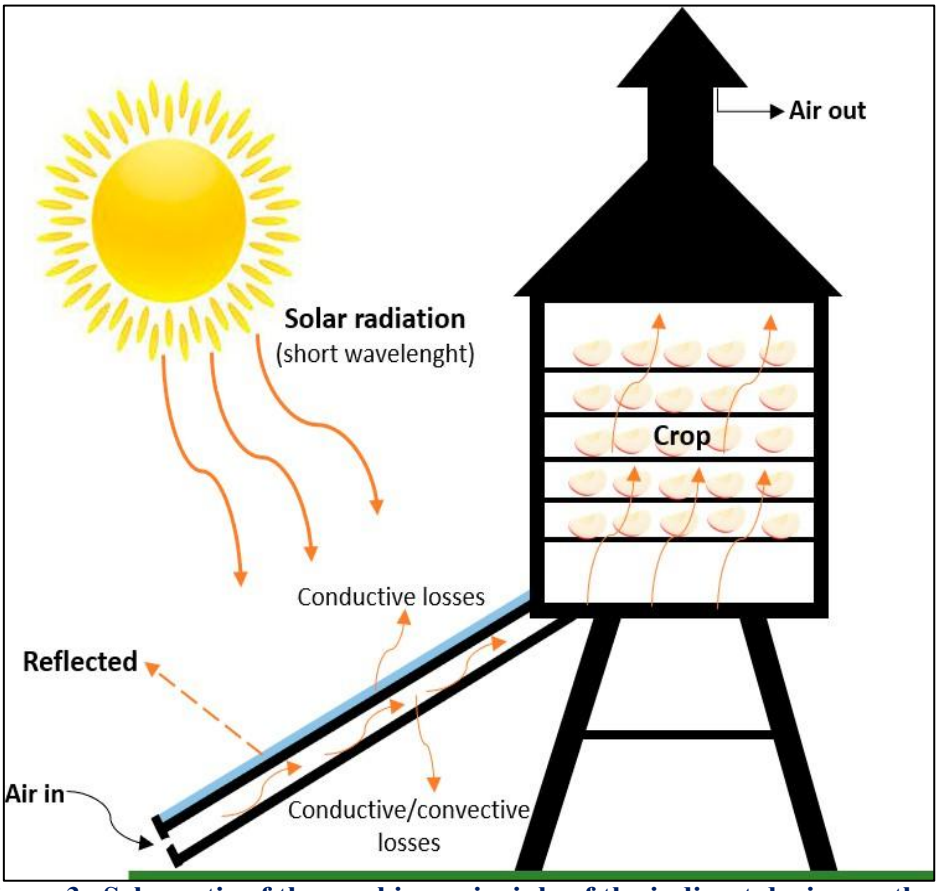

Figure 3. Schematic of the working principle of the indirect drying method.

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system design and environmental dependency.

1. Drying by the sun is very sensitive to the solar radiation, ambient temperature and weather conditions. Seasonal, rainfall, and cloud-cover variations may lead to significant differences in drying efficiency and extend drying time. Such intermittency reduces process reliability and can lead to partial drying or microbial spoilage (Fernandes et al., 2024; Goudjinou et al., 2025).

2. In most cheap solar dryers, temperature and humidity cannot be controlled accurately. High temperatures may destroy heat-sensitive nutrients such as vitamin C, phenolics and antioxidants, whereas low temperatures may lead to incomplete drying and a shortened shelf life (Kumar et al., 2020; Nobossé et al., 2017).

3. Unsuitable airflow system design usually results in imbalanced drying within the trays. Part of the product can be found wet and others become over-dried, making the quality of the products inconsistent and their value in the market lower (Suresh et al., 2025).

4. Medicinal leaves have thermolabile bioactive compounds which are very sensitive to heat, light and oxygen. Temperature and exposure time may cause substantial degradation of flavonoids, phenolics, and antioxidants, thereby lowering their medicinal value (Babarabie et al., 2025; Hegde et al., 2025).

5. The problem is that there are no standardized solar dryer designs that can be applicable to various crops and geographical locations. Different dryer configurations, materials, and operating conditions lead to inconsistent performance and an inability to reproduce results (Fernandes et al., 2024).

6. The majority of conventional solar dryers are manually controlled with no real-time monitoring of the parameters of drying. The absence of automation leads to inefficiencies and augmented labor needs, along with low repeat outcomes (Jalil et al., 2022).

7. Whereas simple types of solar dryers are cheap, modern appliances with sensors, fans and thermal storage devices are expensive to install. This restricts their use, especially in the small-scale farmers and rural areas (Margarita et al., 2018).

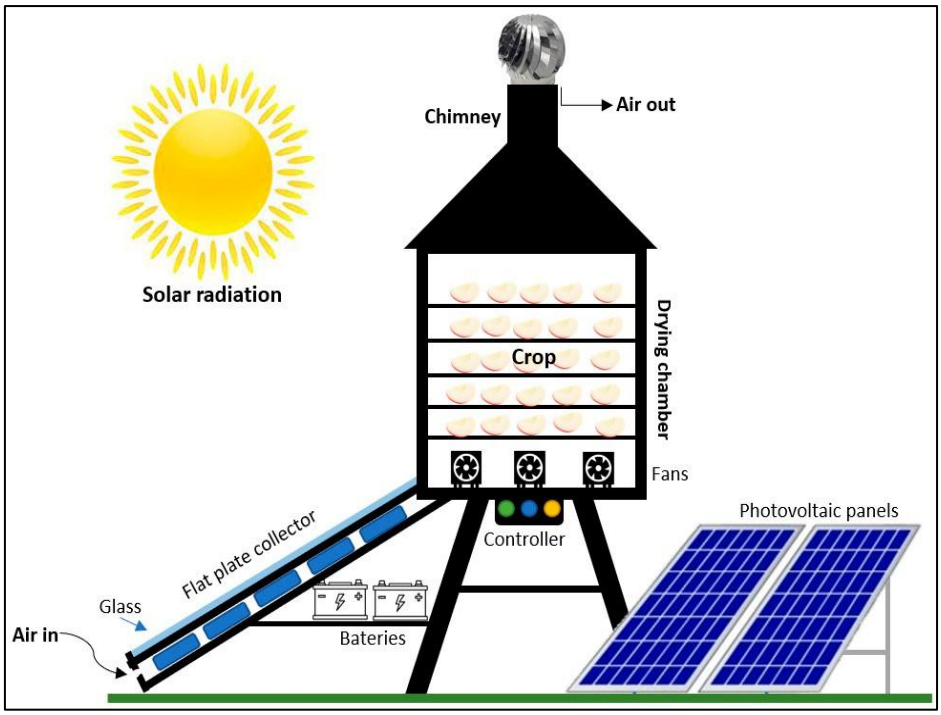

Figure 4. Schematic of the working principle of the hybrid (solar–thermal) drying method.

8. This causes a reabsorption of moisture, contamination and loss of product quality due to improper handling and storage after drying. To ensure that the advantages obtained in the drying process are maintained, proper packaging and storage conditions are necessary.

9. Lack of awareness on the benefits of solar dryers and how the dryer works among farmers and small-scale industries limits the use of solar dryers. The effective use of this technology requires training and transfer of knowledge.

10. Optimization of the best drying conditions in terms of temperature, airflow and drying duration is not simple and is usually carried out through trial and error approaches. This leads to inefficient operations and the use of energy. Such sophisticated optimization tools like RSM and ANN are yet to be adopted (Akter et al., 2022; Sadadou et al., 2021).

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Expected Outcomes and Future Directions

Expected Outcomes

Optimizing solar drying systems for medicinal leaves such as Moringa oleifera is likely to greatly enhance process efficiency and product quality. Among the main effects, the improved preservation of heat-sensitive nutrients, such as vitamin C, phenolics and antioxidants, which are usually destroyed during uncontrolled drying, should be noted (Kumar et al., 2020; Babarabie et al., 2025). With proper management of drying conditions and parameters like temperature, airflow, and drying time, bioactive properties of the leaves can be maintained and effective moisture removal ensured at the same time.

Also, advanced solar dryer designs are expected to enhance drying efficiency, especially the hybrid and active ones. These systems improve heat transfer and airflow distribution, reducing drying time and increasing drying uniformity (Goudjinou et al., 2025). It is predicted that incorporating optimization methods such as Response Surface Methodology (RSM) and Artificial Neural Networks (ANN) will enable the development of predictive models that can precisely estimate optimal drying conditions (Sadadou et al., 2021; Akter et al., 2022).

Energy-wise, solar drying systems will help reduce reliance on traditional energy sources, thereby minimizing energy consumption and environmental impact (Fernandes et al., 2024). Moreover, better management of the drying environment will result in better quality of products in color, texture and shelf life and it will become more commercial and industrial friendly.

Future Directions

The upcoming study on the drying of medicinal leaves with the sun ought to dwell on the incorporation of superior technologies to enhance control and performance of the system. Smart sensors and Internet of Things-based monitoring systems may enable real-time monitoring of drying parameters such as temperature, humidity, and airflow, resulting in more accurate and reliable drying processes (Jalil et al., 2022). Simultaneously, there is a high likelihood of modeling intricate drying behavior and optimizing system operation across different environmental conditions by applying artificial intelligence and machine learning techniques (Sadadou et al., 2021).

The other direction that is significant is the development of thermal energy storage as a means of solving the intermittency of solar energy. These systems may also store excess heat during peak sunshine hours and thus provide uninterrupted drying at night or when the sky is cloudy, thereby enhancing overall performance (Fernandes et al., 2024). Also, standardized, crop-specific solar dryer designs that are easily adjustable across various parts of the world are required.

Nutrient-centric optimization, where preservation of bioactive compounds is considered a main goal, should also be a focus of future research and not only addressing the removal of moisture. Drying performance can even be improved by integrating hybrid renewable energy systems and using advanced materials and enhanced insulation methods. Additionally, post-drying handling, packaging, and storage procedures should be considered to prevent moisture reabsorption and preserve product quality.

Conclusion

Solar drying is a potentially viable and sustainable method for preserving medicinal leaves, such as Moringa oleifera, with high potential to reduce energy use, improve environmental sustainability, and enhance product quality. As mentioned in this review, although traditional drying techniques are easy and cheap, they also entail significant drawbacks, including the inability to control drying conditions, a risk of contamination, and substantial loss of bioactive compounds.

High-tech solar drying systems, such as direct, indirect, mixed-mode, and hybrid systems, offer improved drying performance through enhanced control of temperature, airflow, and moisture removal. These systems have shown the ability to improve the efficiency of drying and the preservation of useful nutrients such as phenolics, flavonoids, and vitamins. Nevertheless, some issues, such as climatic dependence, unstandardization, and low automation, remain obstacles to their popularity.

Optimization methods (RSM and Artificial Neural Networks, ANN) have proven highly promising for enhancing drying performance and predicting optimal operating conditions (Akter et al., 2022; Sadadou et al., 2021). Moreover, recent breakthroughs in the design of solar dryers, such as the inclusion of thermal energy storage and smart sensors and monitors, will improve the system's reliability and efficiency (Fernandes et al., 2024).

To conclude, solar drying is expected to thrive in the future with intelligent, energy-efficient and cost-effective systems that are sensitive to nutrient retention as well as the efficiency of drying. Solar drying will be very instrumental in the sustainable food processing and help to ensure that medicinal plants are put to good use, both in rural and industrial use, by solving the challenges that exist, as well as by incorporating advanced technologies.

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Conflict of interest

None

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